PHEMT Reliability: The Importance of RF Life Testing

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Abstract
PHEMTs have become the technology of choice for current commercial and military system requirements.. A key requirement for all systems is high reliability components which do not fail or degrade in performance during the life cycle of the product. Raytheon employed a stringent set of tests to thoroughly characterize the reliability of its newly transitioned millimeter-wave PHEMT from its 3" research line to its 4" production line. A complete set of tests encompasses both thermal and electronic lifetests. Raytheon's millimeter-wave PHEMT has a lifetime of greater than 1E+07 hours at a channel temperature of 125°C.

Introduction
Solid state power amplifiers (SSPAs) are desired for light weight, small volume, high performance and affordable transmitter applications. The compactness of the SSPA makes it particularly suitable for man portable applications. Long term operation, without need for repair, is a key requirement for the SSPA. In this talk, we address the key reliability issues concerning PHEMT-based SSPAs: limitations of thermal life testing and the importance of RF life testing.

Raytheon uses two types of reliability testing to assess the overall reliability of its power PHEMT MMICs: discrete PHEMT device tests and RF life tests of the final MMIC circuits. (These MMIC circuits would be samples of the actual MMICs used in a system configuration.) For many devices, such as IMPATT diodes, thermal testing accurately predicts lifetime. However, PHEMTs are also subject to electronic failure mechanisms which thermal testing will not induce. Table 1 summarizes the reliability tests that will be described in the following sections.

	Thermal Life test	**RF Life test**
Purpose of Test	Establish reliability of the PHEMT material structure and fabrication process	Establish reliability of a MMIC under system operating conditions
Test Vehicle	Discrete PHEMT	Specific MMIC
Type of Stress	Temperature	Electronic
Failure Criteria	Changes in DC characteristics (Ids or gm)	Changes in millimeter-wave performance (power or gain)
Test Limitation	Temperature stress tests do not uncover all failure mechanisms	Requires several thousand hours of test time

Table 1. Types of PHEMT Reliability Tests

Thermal Life Test
A thermal life test is a conventional test at elevated temperature under DC bias to establish the thermal lifetime of the PHEMT device. The purpose of this test is to determine the fundamental reliability of the PHEMT epitaxial structure and fabrication process. Electromigration of metals, metal/semiconductor contact stability, corrosion and dopant diffusion in

the active layers are examples of thermally induced failure mechanisms that this test will identify. Unlike IMPATT diodes and silicon bipolar transistors, DC accelerated thermal testing is not sufficient for predicting the lifetime of PHEMT devices. RF life testing is also required to uncover additional temperature independent failure mechanisms.

Accelerated thermal life testing establishes thermal lifetime on a statistically significant sample basis in a shorter period of time than would be required for testing at system operating temperatures. Groups of PHEMTs are subjected to elevated channel temperatures (typically 200°-300°C) under DC bias to accelerate temperature-driven failure modes. The average time to failure (MTTF) for each group at a given channel temperature is recorded. The failure criteria is, typically, chosen as a percentage change in either Ids (saturated drain current) or gm (transconductance). The failure time as a function of temperature is shown as an Arrenhius plot from which the failure time at normal operating temperatures can be extrapolated.

A thermal lifetime of greater than 1.0E+08 hours at a junction channel temperature Tj= 125°C has already been established for Raytheon's production 0.25 um PHEMT process (See Figure 1). Other manufacturers of power PHEMT-based devices and MMICs have reported similar projected lifetimes. [1,2]

RF Life test

While thermally accelerated DC tesing is a necessary component in determining operational lifetime, it does not address the electronically-induced failure mechanisms of PHEMT devices. These failure mechanisms can only be determined by performing RF life tests. The second test is a "room temperature" RF life test to determine failure mechanisms associated with operation at microwave or millimeter-wave frequencies under large signal drive. Raytheon and other semiconductor manufacturers [3-5] have observed that a permanent decay in output power over time can occur in power MESFETS and PHEMTs subjected to long term large signal RF drive.

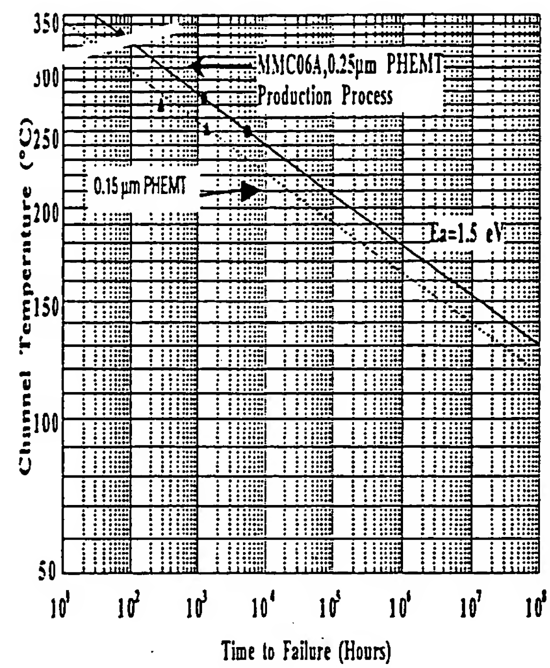

Figure 1. Arrhenius Plot of Raytheon's production 0.25 μm PHEMT (Process MMC-06A) and 0.15μm PHEMT process.

This effect can be the dominant failure mechanism observed in power MMICs. In the proceeding paragraphs, we will discuss the limitations of elevated temperature RF life testing, Raytheon's approach to assessing RF lifetime and methods for improving reliability under RF drive.

<u>Shortcomings of Elevated Temperature RF Life Testing</u>

A major drawback to RF life testing is that it requires several thousand hours of testing to determine the MMIC lifetime. Because of the long testing hours, several GaAs maunufacturer's have tried to accelerate the RF testing using elevated temperature testing. At Raytheon, we intentionally avoid *elevated temperature* RF life testing because high temperature does not accelerate RF-activated failure modes. Furthermore, choosing an appropriate RF

drive level with the device at very high temperatures is difficult because the avalanche component of the breakdown voltage increases with temperature. This causes the negative component of the gate current to decrease at high temperature. The overall result is a net reduction in the RF-induced stress on the MMIC. Due to inherent temperature dependent characteristics (i.e. gm), the MMIC will not be at the same gain compression level at elevated temperatures. Additionally, maintaining the same level of gain compression would require extremely high levels of drive power. For these reasons, it is highly probable that *elevated temperature* RF testing may actually suppress or mask RF-activated failure mechanisms.

Room-temperature RF Life Testing

The RF life test for Raytheon's Q-band power MMIC was conducted as follows. For each MMIC, the drain bias is set at 5 V and the output power is set at the 1 dB compression point at 44 GHz. The initial output power of the MMICs at the 1 dB compression point ranged from 27.5 to 28.3 dBm. Although no external baseplate heating is being used, the MMIC baseplate temperature will reach 30 to 35°C. The relative change in output power (ΔPout) over time (Δt) is monitored. From ΔPout/Δt, the RF lifetime of the MMIC is linearly extrapolated. Results from an RF life test of the three-stage power amplifiers at 44 GHz are shown in Figure 2. The MMIC depicted by the bottom line illustrates the power decay phenomena which occurs during RF drive. This particular MMIC shows a 0.4 dB droop in output power in 2500 hours and 0.8 dB in 6000 hours.
For this particular device the MTTF (failure criteria of ΔPout of 1 dB) would be 1E+04 hrs.

The other four curves shown in Figure 2 received a 250° C stabilization bake for 24 hours in a nitrogen ambient. They showed less than 0.2 dB decay in output power after 3000 hours under drive. The estimated MTTF under RF drive from the sta-baked MMICs would be 1E+05 hours. This corresponds to a lifetime of 12 years (at 100% duty) which is adequate for most system applications.

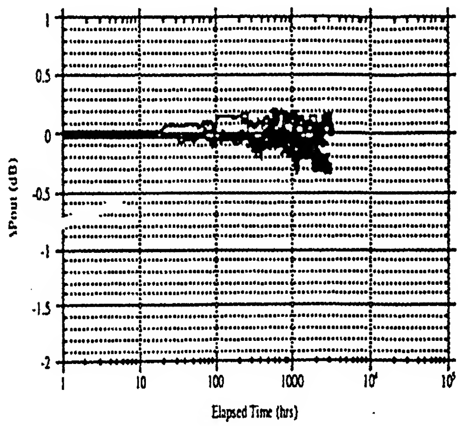

Figure 2. "Room Temperature" RF life test of five 0.15µm PHEMT MMICs. Test conditions: 44 GHz, Vd=5 V, Initial Pout: 27.5 dBm

Improving RF Lifetime

Even though Raytheon's current PHEMT MMICs meet current system reliability requirements, we are still actively seeking approaches to improve the RF lifetime. As suggested by the results in Figure 2, a stabilization bake (sta-bake) appears to offer improvement. The current Raytheon sta-bake is performed at 250°C for 24 hours in nitrogen ambient. The sta-bake time was derived by closely monitoring changes in th[e] DC current-voltage characteristics of discrete PHEMTs during the bake. Aft[er] hours, the DC characteristics showe[d] further changes in open channel c[urrent] reverse breakdown voltage. [P] channel current and reverse [b] voltage are closely coupl[ed] performance.]

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changes and geometrical modifications will also be used to improve PHEMT RF lifetime.

Summary

PHEMTs are new devices offering performance and cost advantages for SSPA applications. However, PHEMT reliability must be fully understood and evaluated for systems applications. Thermally accelerated testing, by itself, is insufficient for establishing PHEMT reliability. Raytheon has determined that a complete lifetime evaluation requires "room temperature" RF life testing.

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